EXPERIMENTAL AND SIMULATION STUDY ON THE EFFECT OF GEOMETRICAL AND FLOW PARAMETERS FOR COMBINED-HOLE FILM COOLING

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Dedicated to my beloved parents, family, lecturers, housemates, graduated members and all my friends.

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ABSTRACT

Film cooling method was applied to the turbine blades to provide thermal protection from high turbine inlet temperatures in modern gas turbines. Recent literature discovers that combining two cylindrical holes of film cooling is one of the ways to further enhance the film cooling performances. In the present study, a batch of simulations and experiments involving two cylindrical holes with opposite compound angle were carried out and this two cylindrical hole also known as combined-hole film cooling. The main objective of this study is to determine the influence of different blowing ratio, M with a combination of different lateral distance between cooling holes (PoD), a streamwise distance between cooling holes (LoD) and compound angle of cooling hole (γ_1/γ_2) on the film cooling performance. The simulation of the present study had been carried out by using Computational Fluid Dynamic (CFD) with application of Shear Stress Transport (SST) turbulence model analysis from ANSYS CFX. Meanwhile, the experimental approach makes used of open end wind tunnel and the temperature distributions were measured by using infrared thermography camera. The purpose of the experimental approach in the present study is to validate three cases from all cases considered in the simulation approach. As the results shown, the lateral coverage was observed to be increased as PoD and γ_1/γ_2 increased due to the interaction between two cooling air ejected from both cooling holes. Meanwhile, film cooling performance insignificantly changed when different LoD was applied. As the conclusion, a combination of the different geometrical parameters with various flow parameters produced a pattern of results. Therefore, the best configuration has been determined based on the average area of film cooling effectiveness. For M = 0.5, PoD = 1.0, LoD = 2.5 and $\gamma_1 / \gamma_2 = -45^o/+45^o$ case is the most effective configuration. In the case of M = 1.0 and M = 1.5, PoD = 0.0, LoD = 3.5, $\gamma_1 / \gamma_2 = -45^o/+45^o$ and PoD = 0.0, LoD = 2.5, $\gamma_1 / \gamma_2 = -45^o/+30^o$ are the best configurations based on the overall performance of film cooling.

ABSTRAK

Teknik filem penyejukan telah digunakan untuk bilah turbin bagi membekalkan perlindungan daripada suhu yang tinggi di dalam turbin gas moden. Kajian baru-baru ini mendapati gabungan dua lubang silinder filem penyejukan adalah salah satu cara untuk meningkatkan lagi prestasi filem penyejukan. Simulasi dan eksperimen yang melibatkan dua lubang filem penyejukan berbentuk silinder dengan sudut lubang yang bertentangan telah dijalankan di dalam kajian ini dan dua lubang silinder tersebut juga dikenali sebagai filem penyejukan lubang gabungan. Objektif utama kajian ini adalah untuk mengkaji pengaruh nisbah tiupan, M dengan gabungan jarak antara dua lubang penyejukan pada paksi z (PoD) dan paksi x (LoD) serta sudut lubang filem penyejukan (γ_1/γ_2) pada prestasi filem penyejukan. Pendekatan simulasi dalam kajian ini menggunakan Pengkomputeran Dinamik Bendalir (CFD) dengan mengunakan model gelora *Shear Stress Transport* (SST) daripada *ANSYS CFX*. Manakala, dalam pendekatan eksperimen, terowong angin jenis hujung terbuka telah digunakan dan taburan suhu telah diukur dengan menggunakan kamera termografi inframerah. Eksperimen telah dijalankan dalam kajian ini bagi mengesahkan salah satu kes daripada semua kes yang dipertimbangkan dalam pendekatan simulasi. Hasil kajian ini menunjukkan bahawa liputan penyejukan yang lebih luas telah dilihat apabila PoD dan γ_1/γ_2 meningkat. Manakala, prestasi filem penyejukan hanya mengalami sedikit perubahan apabila LoD yang berbeza digunakan. Sebagai kesimpulan, gabungan parameter geometri yang berbeza bersama parameter aliran menghasilkan corak keputusan yang berbeza-beza. Oleh itu, konfigurasi yang terbaik telah ditentukan berdasarkan purata kawasan filem penyejukan yang berkesan. Untuk M = 0.5, PoD = 1.0, LoD = 2.5 dan $\gamma_1 / \gamma_2 = -45^o/+45^o$ adalah konfigurasi yang paling berkesan. Manakala dalam kes M = 1.0 dan M = 1.5, PoD = 0.0, LoD = 3.5, $\gamma_1 / \gamma_2 = -45^o/+45^o$ dan PoD = 0.0, LoD = 2.5, $\gamma_1 / \gamma_2 = -45^o/+30^o$ adalah konfigurasi yang terbaik berdasarkan prestasi keseluruhan filem penyejukan.

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LIST OF SYMBOLS AND ABBREVIATIONS

q	-	Heat
v	-	Velocity
w	-	Work
ρ	-	Density
∞	-	Mainstream flow
T_{aw}	-	Adiabatic wall temperature
T_∞	-	Mainstream temperature
T_2	-	Cooling air temperature
T_3	-	Turbine inlet temperature
T_4	-	Turbine outlet temperature
Tu	-	Turbulence intensity
η	-	Film cooling effectiveness
C_p	-	Total pressure loss coefficient
CFD	-	Computational Fluid Dynamic
D	-	Hole diameter
y_1	-	Compound angle of upstream cooling hole
y_2	-	Compound angle of downstream cooling hole
LoD	-	Streamwise distance between two holes of combined-hole
PoD	-	Lateral distance between two holes of combined-hole
Re	-	Reynolds number
M	-	Blowing ratio
RMSE	-	Root mean square error

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Gas turbine is one of the most popular heat engine used in power generation industry. One of the attractive features is capability of the gas turbine to operate using various fuels such as crude oil, liquefied natural gas (LNG), naphtha, kerosene and diesel. Besides its application in electricity generation, gas turbines also used to generate power for aircrafts, ships and trains. Figure 1.1 shows the example of modern gas turbine involving four main sections; compressor, combustion chamber, turbine and exhaust.

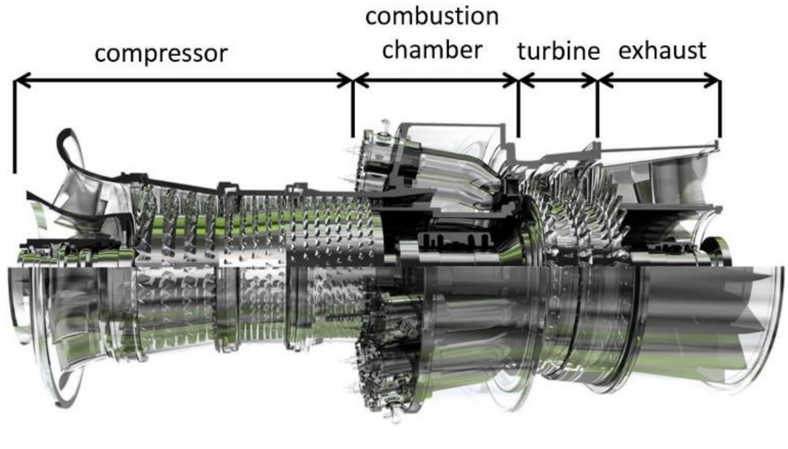


Figure 1.1: Modern gas turbine [1]

In principal, gas turbine make used of Brayton cycle as its working cycle. As shown in Figure 1.2, the cycle involves four processes; compression, heat addition, expansion and heat rejection. In the compression process, the fresh air is drawn into the compressor where the temperature and pressure of the air is raised. The compressed air is then introduces into the combustion chamber and mixed with the fuel which is injected through the nozzles. The fuel-air mixture then ignited under constant pressure conditions to complete the heat addition process through converting the chemical energy of the fuels to flow energy of the combustion gases. Hot combustion gases then expands through the turbine while producing mechanical energy in terms of rotating shaft. The expanded combustion gas is then rejected to the ambient.

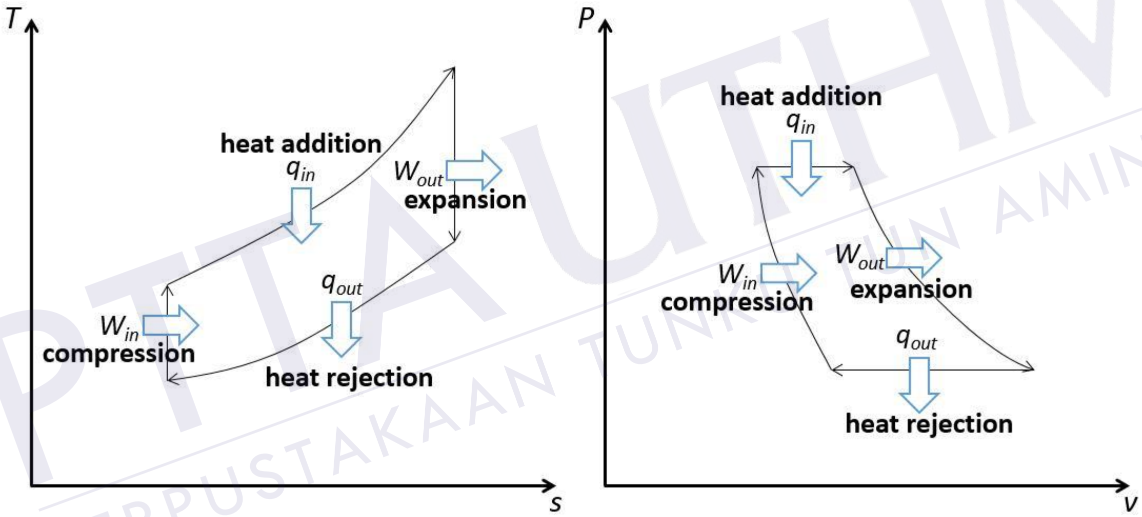


Figure 1.2: *T*-*s* and *P*-*v* diagram for Brayton cycle [2]

The overall thermal efficiency of Brayton cycle which applied on gas turbine can be determine through Eq. 1.1. Based on the equation, the overall thermal efficiency is directly proportional to the turbine inlet temperature. The increase in the turbine inlet temperature not only improve the overall efficiency, but also allow higher power output of the gas turbine.

$$\eta_{Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{T_4}{T_3} \tag{1.1}$$

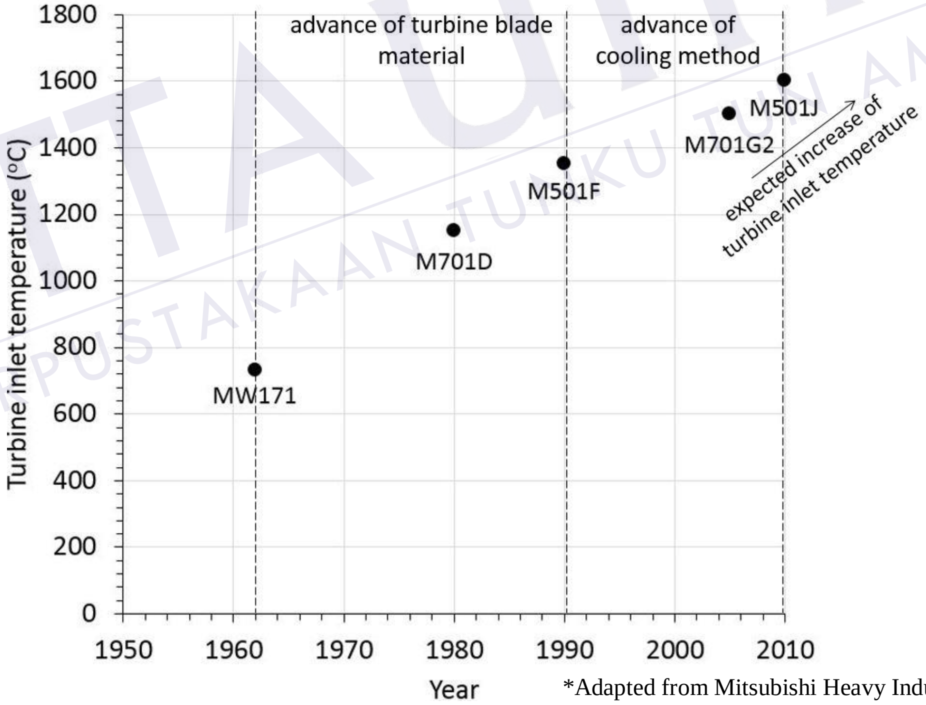
where, w_{net} - net work [Watt]

q_{in} - total heat input [Watt]

T_3 - turbine inlet temperature [K]

T_4 - turbine outlet temperature [K]

Figure 1.3 shows the pattern of turbine inlet temperature for different gas turbine produces by Mitsubishi Heavy Industries (MHI) along the year 1962 to 2010. The turbine inlet temperature has increased tremendously in comparison with its early design. During its early days in 1940s, the turbine inlet temperature was limited to be around 540 ^{o}C. This limitation is due to the metallurgical reason whereby the available blade material at that time inhibit higher operational temperature of the gas turbine.



*Adapted from Mitsubishi Heavy Industries

Figure 1.3: Turbine inlet temperature of MHI gas turbines series [3]

The early progress in achieving higher overall thermal efficiency of a gas turbine via increase in turbine inlet temperature have been propelled by the introduction of new materials which capable to sustain at higher temperature. These materials allow the gas turbine manufacturer to have much more durable blades to be applied in gas turbine. In the late 90's, the introduction of cooling technique into turbine blade design helps to further increase the turbine inlet temperature. Combination of various cooling techniques such as impingement cooling, convection cooling and tip cap cooling lead to a highly sophisticated cooling system which can be commonly found in today modern gas turbine. The modern gas turbine operates in the range of 1200 ^{o}C to 1600 ^{o}C which is expected to further increase in the coming future.

1.2 Background of study

Nowadays, the modern gas turbine operates in very high temperature range and is expected to increase in upcoming future. This high operating temperature has improved the overall efficiency and allow higher power output of the gas turbine. However, due to high operating temperature, the turbine components particularly the blades are exposed to high thermal loads which compromise its operational durability. Therefore, enhancements of thermal protection on critical surfaces are required to ensure not only the reliability but also lowering the maintenance cost of the gas turbine engine.

Cooling techniques have been introduced and studied in the last few decades to improve thermal protection of a turbine blade. Various cooling techniques have been introduced such as internal cooling which involves convection cooling, impingement cooling and transpiration cooling, while film cooling as external cooling. Each cooling technique has their own advantages and the combination of these techniques developed a sophisticated cooling system of the turbine blades.

Film cooling is an external cooling technique which provides a thin layer of cooling air on the critical section of the blade surfaces. This layer also prevents direct contact between the high temperature stream and the blade surface. The protective layer allows the turbine to operate at very high temperature thus improve the overall performance of the gas turbine. Figure 1.4 shows the example of turbine blade together with details on internal and external cooling techniques.

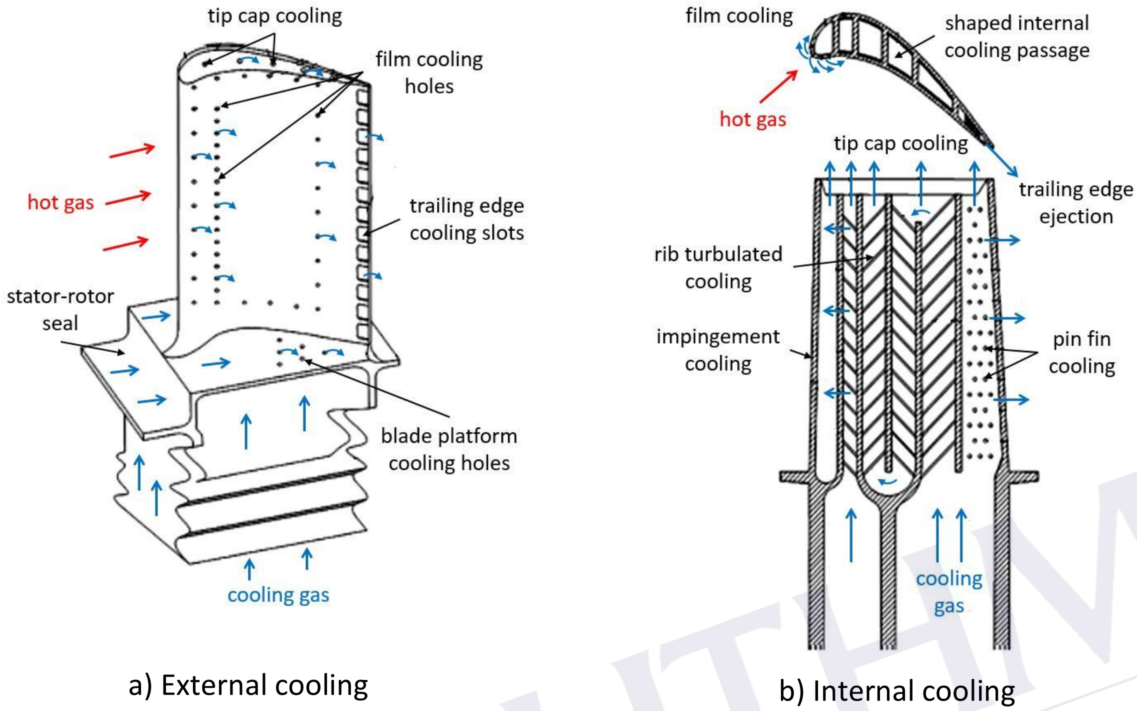


Figure 1.4: Turbine blade with various cooling techniques [4]

The early introduction of film cooling hole involves a discrete cylindrical hole. This particular hole design has been widely used even in the modern gas turbine blade design due to its manufacturability [3-5]. Other designs of film cooling hole have been also introduced aims to improve the effectiveness of film cooling hole. Fan-shaped film cooling hole, laidback film cooling hole and trench film cooling hole [6-9] are some example of other design of film cooling hole.

Fan-shaped and laidback film cooling hole designs are characterized by the expanded cooling hole exit in comparison to cylindrical film cooling hole. Cooling air ejected from these types of cooling holes appears to have better lateral spread thus producing better performance in comparison with the cylindrical hole. On the other hand, trench film cooling hole design has a small ditch which placed above the film cooling holes with specific width and depth. By adding the small ditch (trench), cooling air was covering the surface in streamwise and spanwise direction and improving the cooling performance.

In addition to the aforementioned designs, researchers also study the effect of combined-hole film cooling. Among them is Ahn et al. [10] where the research focus on the arrangement of two rows of the cylindrical hole with opposite orientation angle. Kusterer et al. [11] also combined the cylindrical hole with various compound angle and distance between two cylindrical holes. Both of the works indicate better film cooling performance compared to the other film cooling hole design. Hence, many studies [12, 13, 14] were carried out related to the combined-hole film cooling because its involved combination of two simple cylindrical holes which simpler to manufacture in comparison with the laidback or fan-shaped film cooling hole.

1.3 Problem statement

Among the early works on combined-hole film cooling is the work by Han et al. [15]. It has been reported that combined-hole film cooling with opposite compound angle produced better performance by providing wider lateral coverage. Kusterer et al. [16] also indicate that combined-hole film cooling provides better lateral coverage after comparing with fan-shaped film cooling hole.

The combined-hole film cooling was introduced by combining two cylindrical holes with opposite compound angle to overcome and weaken the formation of kidney vortex while improving the film cooling performance. By combining two cylindrical hole, the anti-kidney vortex was produced and counter the formation of kidney vortex which attracts hot mainstream air to the bottom of cooling air. In combined-hole film cooling system, it is observed that the anti-kidney vortex produced are controlled by the distance between cooling holes and compound angle of the cooling holes. The distance between cooling holes determines the formation of anti-kidney vortex led by the interaction between two vortices, while the compound angle affects the strength of each branch of the anti-kidney vortex.

In the work of Han et al. [15], the geometrical parameter of the distance between cooling holes and compound angle of the cooling holes were considered and varied to observe the effects on the film cooling performance. However, both geometrical parameters lead to an asymmetrical flow structure due to the uncertain behaviour of the anti-kidney vortex. This condition also causes the film cooling effectiveness along the streamwise direction inclined towards one side and leave another side less protected. Therefore, some improvement were needed to overcome the asymmetrical flow structure and improve the overall performance of combined-hole film cooling. Further improvements could possibly achieve by adding and varying the geometrical and flow parameters of combined-hole film cooling. It is possible if the geometry parameters and flow parameter match well on the local flow structure.

1.4 Important of study

The present study intended to explore various geometrical and flow parameters to provide more information on the thermal performance of combined-hole film cooling. Simulation and experimental approach were consider in the present study to compare and validate the results between the two different approaches. The information of film cooling performance, flow structure and optimal arrangement of combined-hole film cooling will be used as the reference for the future study.

1.5 Objective of study

The objectives of this study are:

a) To predict the film cooling effectiveness of combined-hole using Computational Fluid Dynamic (CFD);
b) To validate the predicted film cooling effectiveness by CFD with the experimental results;
c) To determine the influence of geometrical parameters on the film cooling performance of combined-hole;
d) To determine the influence of flow parameters on the film cooling performance of combined-hole

1.6 Scope of study

The scopes of the present study were divided into two parts; experimental and simulation. For the experimental work, the open end wind tunnel was considered as the main source of the mainstream air. Mainstream air flowed inside the wind tunnel was set at 22.0 m/s which produce Reynolds number of 4200. For the cooling air, a blower was used to supply the cooling air with a moderate increase of pressure. The cooling air was supplied through the air heater and venturi meter before entering the plenum and flow out through the film cooling hole. The infrared thermography camera was used in the present experimental work to observe the temperature change on the test plate surface.

For the simulation work, the analysis of ANSYS CFX from Computational Fluid Dynamics was considered with the application of Shear Stress Transport (SST) turbulence model. Steady state simulation was applied in the present simulation work and the auto timescale was used together with RMS residual target value of 1×10^{-4}. Minimum iterations were set at 100 iterations while maximum iterations were set at 300 iterations to complete the simulation process. There is some constant variable considered in the present simulation work; Reynolds number set at 4200, mainstream air temperature set at 300K and cooling air temperature set at 310K.

For both experimental and simulation works, several flow and geometrical parameters was considered. For flow parameter, the blowing ratios are varied at three different value; 0.5, 1.0 and 1.5. Similarly three geometrical parameters were considered as below:

a) Lateral distance between two holes of combined-hole unit divide by hole diameter, PoD was set at 0.0D, 0.5D, 1.0D
b) Streamwise distance between two holes of combined-hole unit divide by hole diameter, LoD was set at 2.5D, 3.0D, 3.5D
c) Compound angle of cooling hole, γ_1 / γ_2 was set at -30°/+30°, -45°/+45°, -60°/+60°, -45°/+30°, -60°/+45°

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